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A simulation framework for the dynamic assessment of energy policy impacts on customer PV-battery adoption and associated energy market impacts

Kelvin Say[a]*, Michele Rosano[a]

[a]Sustainable Engineering Group, Curtin University, Kent Street, Bentley, 6102, Australia

Abstract

As energy systems undergo significant utility-scale transitions to combat global warming, the capacity for future customers to lead the next transition needs to be studied and quantified. This research presents a customer-driven energy policy simulation framework that integrates endogenous customer PV and battery investment, the energy market and generators, with the means to comparatively evaluate market evolution and policy impacts. Energy policies can also be designed and tested within this framework to assess the potential for customer-driven renewable energy transition pathways. A hypothetical analysis is presented.

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Keywords: PV battery systems; distributed energy resources; techno-economic analysis; energy scenarios;

1. Introduction

The rate of technological and economic changes brought about by renewable energy technologies continues to challenge policy makers. These changes to the energy market have exposed existing generation and network assets to significant utility-scale operational and planning uncertainties [1]. At the same time, the falling installation costs of solar PV and Battery Energy Storage Systems (BESS) has encouraged significant customer investment in behind-

* Corresponding author. Tel.: +61-8-9266-9974
E-mail address: kelvin.say@curtin.edu.au

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the-meter energy generation (and to a lesser extent energy storage) that has started to impact network energy demand and daily operation.

Utilizing simulation (rather than optimization) modelling for network and energy system planning allows multiple evolutionary pathways to be evaluated. By considering customers as the basis for network energy demand, the market pressures from customer PV and battery investments can be modelled. A rich literature exists that utilize techno-economic modelling to evaluate system sizing [2], electricity prices [3], feed-in tariffs [4] and load profiles [5] on PV and battery adoption. Integrating socio-technical perspectives into investment decisions [6] allows a broader range of issues to be studied.

This modelling framework incorporates these dimensions into a simulation of customer behavior and energy market responses, to evaluate market evolutionary pressures and policy impacts. Policy instruments that affect customer renewable energy investment can be evaluated, from the individual customer through to network and market levels. Furthermore, policies can be designed and tested within this framework to assess the potential for customer-driven renewable energy transition pathways.

2. Customer-driven energy policy simulation framework

At the center of the simulation framework is a bottom-up evaluation of customer energy demand profiles. Aggregating the results produces a forecast of network demand that allows the assessment of market and generator outcomes. By evaluating across a range of policy scenarios, the effectiveness and sensitivity of changes to policy instruments can be estimated. Endogenous customer PV-battery investment decisions allow this framework to dynamically adapt to changing financial investment conditions.

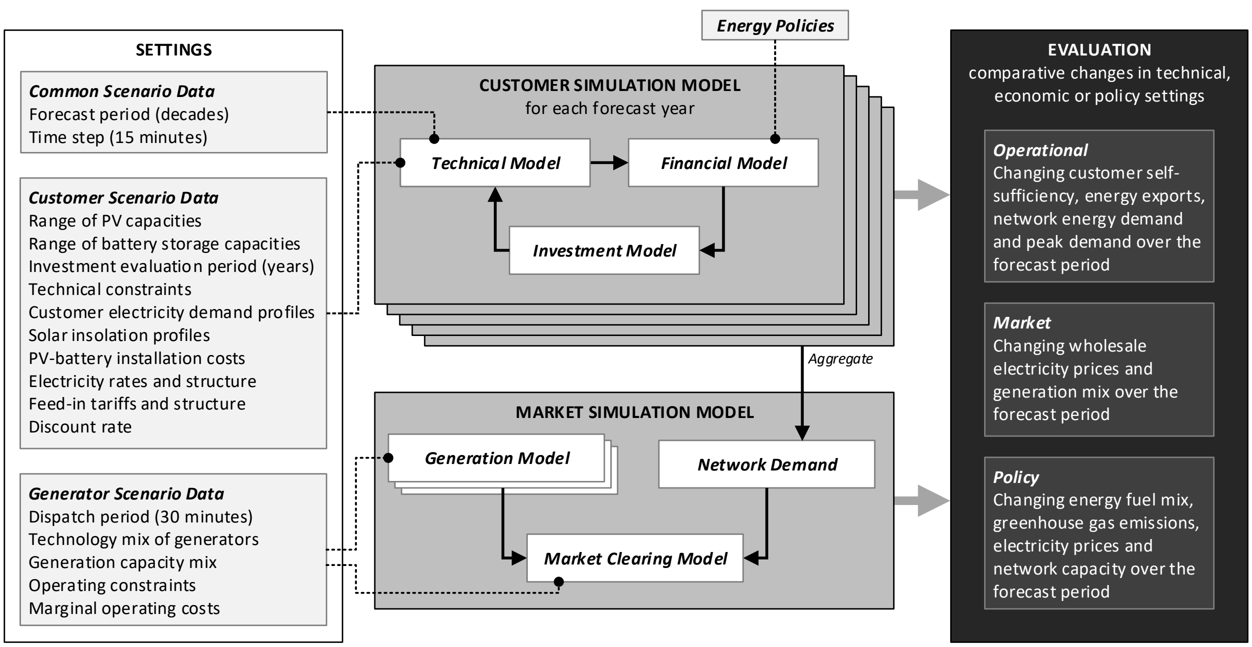

Fig. 1. Customer-driven energy policy simulation framework

The simulation framework consists of two major components, the *customer simulation model* and *market simulation model*. The *customer simulation model* independently evaluates each and every customer's unique demand profile to forecast individual energy demand, while the *market simulation model* uses the aggregate customer simulation data to evaluate the market impacts.

2.1. Customer simulation model

The *customer simulation model* forecasts future net energy demand for each customer by determining (i) the most economic PV and battery system configurations, and (ii) when to install a PV and/or battery system. By analyzing a large set of customers and aggregating their results, a forecast of grid demand can be produced. Energy policies that affect customer financial returns (such as feed-in tariffs, electricity prices and rate structures) and economic conditions (such as PV and battery installation costs) that affect customer investment decisions, can be evaluated simultaneously. Furthermore, as the scenario's financial conditions change, customer investment decisions respond dynamically and lead to further changes in grid demand. The simulation results provide the means to forecast grid demand, regime shifts and tipping points between customers and utilities. This model facilitates the evaluation of customer-led grid and policy outcomes. The customer dynamics are generated using three interacting elements, the *technical model*, *financial model* and *investment*.

2.1.1. Technical model

The *technical model* utilizes a customer's electricity demand profile and obtains the operational impact from the installation of each PV and battery system combination for the length of the investment evaluation period. This information is required by the *financial model* for PV and battery investment analysis. The *technical model* utilizes a multi-staged approach and uses a customer's energy demand profile to calculate (at each 15-min timestep) the amount of energy generated, imported, exported, stored and discharged. The solar PV generation profiles can be scaled using location-specific solar insolation profiles and modelling performance degradation. By subtracting the solar generation curve from the customer's electricity demand a preliminary net energy profile is produced, that is used by the BESS model to determine its charge and discharge dynamics. The BESS model takes into consideration the operational lifespan, capacity degradation and option of grid-charging. The final net energy profile from the BESS model represents the bi-directional flow of energy at the customer energy meter and determines the annual imported and exported energy for each potential PV and/or battery system investment option.

2.1.2. Financial model

The *financial model* uses data from the *technical model* coupled with changing *market conditions* and *energy policies* to determine the economic returns from each PV and/or battery investment. Typical retail electricity rate structures consist of a volumetric usage charge ($/kWh), daily supply charge ($/day) and volumetric feed-in tariff rebate ($/kWh), the operational data from the *technical model* can be used to calculate the annual electricity bills across the investment evaluation period. Any electricity bill savings then equate to cash flow received from each PV and battery investment. Financial metrics, such as net present value (NPV), discounted payback period, internal rate-of-return (IRR) and return-on-investment, can be calculated by the *financial model*. As electricity prices, feed-in tariffs and installation costs of PV and battery systems change over time, the *financial model* dynamically responds and changes the financial returns on each PV and battery investment. Hence the *financial model* provides the means to evaluate (with respect to each customer's electricity demand profile) when and how PV-only, PV-battery or battery-only systems become economic.

2.1.3. Investment Model

For each forecast year, the *investment model* uses the *financial model* data to decide if a customer should or shouldn't install a PV-only, PV-battery or battery-only system. Individual financial metrics (such as the maximum NPV or lowest payback period) can be used to determine when to invest. Alternatively a multi-staged approach, such as Norm Activation Theory (NAT) can be used [7]. NAT requires a customer to be firstly aware of the investment opportunity before deciding to invest. This approach has the added benefit of integrating both financial and socio-technical perspectives into customer investment behavior.

If a PV-only, PV-battery or battery-only system is installed, the customer's electricity demand profile is updated to reflect the installation of the new equipment. This leads to a new set of investment opportunities that have to complement the newly installed equipment. Overall the *customer simulation model* provides the means to forecast energy demand at the individual and aggregate levels.

2.2. Market simulation model

The sum of net customer energy demand from the *customer simulation model* generates a time-series forecast of the network demand in the energy market. By using a market clearing method, such as economic merit-order dispatch, the *market simulation model* determines the dispatching generators within each dispatch period. As the market clearing mechanism in the *market simulation model* operates under perfect information, care must be taken to avoid short-term evaluations, like network constraints and frequency control services, but rather consider longer-term perspectives, such as annual changes to network demand. Additionally, more sophisticated market simulation models can also be utilized if the model is able to accept the forecasted customer energy demand from the *customer simulation model*. The hard-link between the energy market and customer simulation models facilitate the bottom-up customer-led evaluation of energy policy and economic conditions.

2.3. Evaluation

The proposed framework provides researchers with the means to *operationally* forecast and evaluate customer installations of PV and BESS. Utility-scale solar PV network integration issues have been well observed [8], however as customer-sited BESS significantly change customer interactions across many points across the grid, the operational dynamics become more difficult to predict. By aggregating results across a large range of real or hypothetical customer energy demand and solar insolation profiles, a network demand forecast is created that incorporates customer PV and battery installations while facilitating a wide range of additional operational assessments, such as changes to annual energy consumption and peak network demand, shifting of peak demand hours and changing ramping rates. Furthermore, excess solar PV and underutilized energy storage can be quantified to evaluate the supply and demand potential for demand side management schemes.

The framework also creates a simulated environment to assess *market* opportunities and risks arising from these customer-driven changes. The hard-link between the customer and market simulation models provides a view on the technical and financial flows in the energy market and allows for the evaluation of micro-economic transactions between customers, the energy market and generation assets. By utilizing a market clearing mechanism with forecasted energy demand, the suitability of various generation technologies to meet the network demand can also be evaluated. Additionally, generation and network capacity planning can be assessed by evaluating the peak network demand and energy consumption operational results.

Policy instruments, such as feed-in tariffs, surcharges and rebates, shape customer investment decisions. The operational and market simulations allow this framework to assess the effectiveness of these policy instruments to achieve policy goals, such as greenhouse gas emission reduction from changes to the utility-scale fuel mix and greater customer self-generation and consumption.

3. Hypothetical analysis

This hypothetical analysis aims to ‘determine a timeline of customer solar PV and battery capacity installations, the impact on the network energy demand and influence on energy market revenues’. The scenario consists of an ideal network containing 50 unique residential customers using 5 Australian energy consumption profiles (‘double hump’, ‘day focus’, ‘nigh focus’, ‘evening focus’ and ‘high day & evenings’) [9] that have been scaled to an annual energy consumption between 2 and 10 MWh/annum. The analysis runs over a 30-year forecast period where customers use an investment evaluation period of 10 years. Based on electricity prices in Perth, Australia, the fixed-rate electricity usage charge, fixed network charge and feed-in tariff are 27 c/kWh, 95 c/day, 7 c/kWh respectively and increase at 5% each year. Furthermore, the feed-in tariff is only eligible to customers with installed PV up to 5 kW_P [10]. A discount rate of 6% is used. The installation cost of solar PV and battery systems start at \$2000/kW_P [11] and \$1500/kWh [12] respectively and decrease at -5.9% [13] and -8% [14] each year. The PV model has a 25-year operational lifespan with an end-of-life capacity of 80%. The BESS model, based on a Tesla Powerwall 2, has a

10-year operational lifespan, 100% depth-of-discharge and an end-of-life capacity of 70%. As it not cost-effective under flat-rate volumetric usage charges, grid-charging is disabled. The solar insolation profile is obtained from the PV Watts calculator for Perth, Australia with a fixed north-facing roof mounted array (20° tilt) that receives an average solar radiation of 5.82 kWh/m^2/day [15].

The *investment model* utilizes two stages, based upon 'customer awareness' and 'customer behavior'. The 'customer awareness' for an investment occurs when *any* potential PV and/or battery investment has a discounted payback period less than 5 years. Once the awareness has been established, the 'customer behavior' governs which PV and/or battery system is installed. In this analysis, the system configuration with the maximum NPV is chosen (Fig. 2).

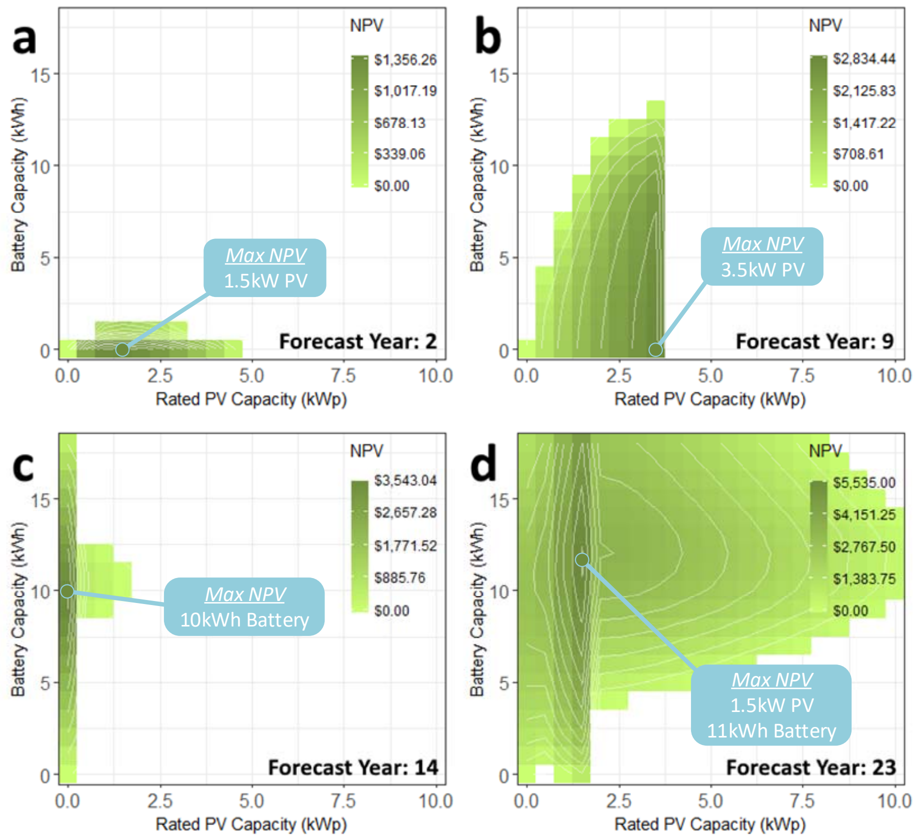

Fig. 2. Net Present Value (NPV) investment with a 10-year investment horizon of each PV-battery combination that leads to a decision to invest in (a) forecast year 2, (b) forecast year 9, (c) forecast year 14, (d) forecast year 23

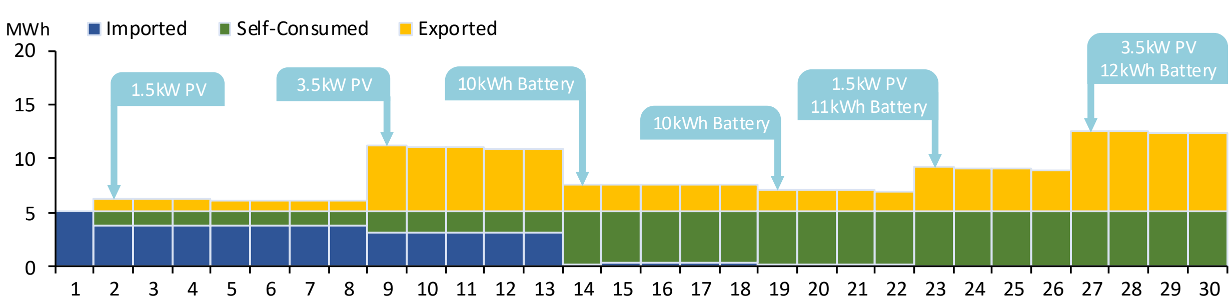

Fig. 3. Forecasted changes to one of the customer's net energy demand with installed PV and battery systems

The results for a single customer with a 'double hump' profile and an annual consumption of 5.2 MWh are presented in Fig. 3. A 1.5 kW_P PV system is initially installed in the 2nd year. In the 9th year, a 3.5 kW_P PV is added for a combined total of 5 kW_P and maintaining the eligibility for the feed-in tariff (FiT). In the 14th year, battery prices have fallen enough to add a 10 kWh BESS. Interestingly after only 5 years, it is cost effective for the customer to install another 10 kWh battery system rather than wait for the initial BESS to reach its end-of-life. As the original 1.5 kW_P PV nears its end-of-life in the 23rd year and PV and battery costs have fallen far enough that losing the FiT rebate (by exceeding the 5 kW_P limit) is no longer an effective financial disincentive for larger PV systems. From this point on, it becomes increasingly cost-effective to reduce overall grid-consumption with even larger PV and battery systems.

By aggregating each customer's timeline of PV and battery investments, a network wide perspective of energy supply and demand is obtained. In this scenario, *all* customers eventually find it cost-effective to install BESS that significantly reduce self-consumption to a fraction of their original consumption (Fig. 4a). Once this occurs, the network grid energy demand falls significantly and never recovers (Fig. 4b).

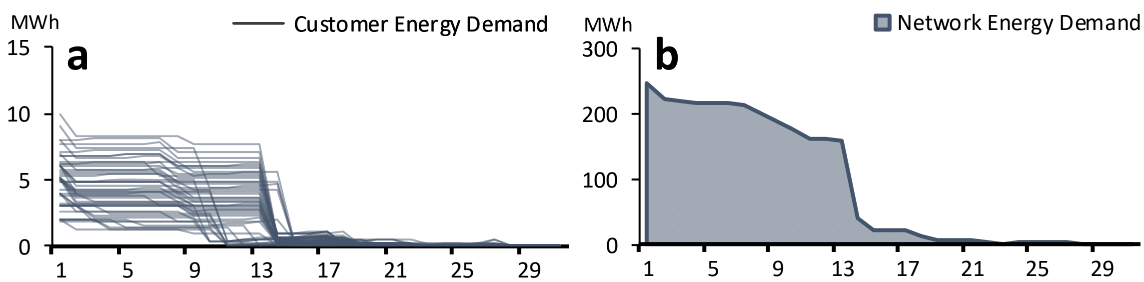

Fig. 4. Forecasted changes to grid energy demand and energy exports at the (a) customer-level (b) network-level

The capacity forecast for customer PV and battery systems (Fig. 5a) shows that once BESS become cost-effective, customer PV-battery systems will become the norm and rather than plateauing, increasing amounts of PV and BESS capacity will become available on the grid. A forecast of retail electricity revenues is generated (Fig. 5b) by computing the sum of all customer electricity bills (using their annual imported and exported energy quantities). Not surprisingly, the results indicate that as customers significantly reduce grid imports the volumetric contribution becomes negative and fixed charges become the biggest contributor to future revenue.

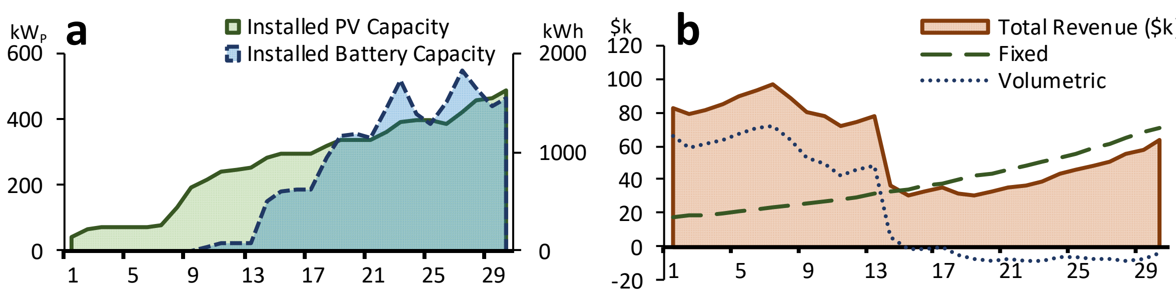

Fig. 5. Forecasted changes to (a) installed customer PV and battery capacity (b) aggregate customer retailer revenues

The hypothetical analysis suggests that all 50 customers will eventually find it economic to install enough PV and battery capacity to significantly reduce their grid imports. Notably, the tipping point (around forecast year 13) is consistent across different customer energy profiles and annual consumption quantities (granted the sample size is small).

4. Conclusion

Energy policies that affect the economics of PV-battery investment (such as FiTs, rate structures, surcharges and rebates) can be designed and tested within this framework – and it allows energy researchers to assess the potential for customer-driven renewable energy transition pathways. The presented hypothetical analysis illustrates a single scenario that leads to significant reductions in customer grid demand. However, a comparative assessment approach across scenarios allows researchers to quantify and assess the *relative* influence of policy changes (such as various FiT rates or renewable energy surcharges) on the time and quantity of potential customer PV and battery adoption. The results from this approach highlights energy market and utility generation impacts while providing an awareness of future trading conditions. Furthermore, this framework allows the simulation and development of new energy market concepts that can better capture the value in customer-sited distributed energy resources that have the potential to reduce the cost of electricity for all customers.

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